Pacemakers of extreme floods during warmer and wetter climates of the “Wild Nile” stage

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Article

Keywords:

Posted Date: November 14th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3051876/v1

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Additional Declarations: There is NO Competing Interest.
Version of Record: A version of this preprint was published at Nature Geoscience on July 3rd, 2024. See the published version at https://doi.org/10.1038/s41561-024-01471-9.
Pacemakers of extreme floods during warmer and wetter climates of the “Wild Nile” stage

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Abstract: Understanding how large river systems will respond to an invigorated hydrological cycle as simulated under higher global temperatures is a pressing issue. We present here a 1500 yr-long annually-laminated (varved) record that tracks the seasonal discharge of the Nile River during the wetter- and warmer-than-present Early Holocene. This unique record depicts the mobilization of large amounts of sediments during strong summer floods that probably rendered the Nile valley inhabitable. More frequent and rapid switching between extreme (strong and weak) floods between 9.2 and 8.5 ka BP indicate highly instable fluvial dynamics. On interannual timescales, flood variability is paced by El Niño-Southern Oscillation while multi-decadal oscillatory modes drive the changes in extreme flood events. These pacemakers are also identified in Nile flow records from the Common Era, which demonstrates their stationarity under different climatic conditions.
One-Sentence Summary:
Past warmer and wetter conditions in North Africa led to much stronger-than-present floods and increased annual variability of the Nile River flow.

Main Text:
The Nile River is an iconic waterway that has connected the humid tropics of Africa to the semi-arid Mediterranean coast and sustained the establishment of complex societies for many millennia. Today, the Nile discharge is mainly controlled by seasonal migrations of the African summer monsoon, bringing high amounts of rainfall to the Ethiopian Highlands in summer. Recent episodes of droughts or extreme rainfall bear serious consequences for communities living in densely populated areas along the Nile course. Global climate models participating in the Coupled Model Intercomparison Project (CMIP) forecast wetter conditions in Eastern Africa as well as an increase in both magnitude and frequency of extreme rainfall events in warmer climates. Enhanced and more extreme rainfall will likely cause strongly variable and intermittent Nile river runoff, which poses serious challenges for water management (i.e., storage and distribution) and social stability. However, the CMIP model ensemble used to simulate the Nile response to global warming shows a wide range of possible scenarios, leading to highly uncertain forecasts and potentially to the adoption of inadequate adaptation measures.

In order to test model simulations and evaluate the response of the Nile River to warmer and wetter conditions, we used a unique annually-resolved sediment archive from offshore the Nile mouth deposited during the Holocene African Humid Period (AHP). This period provides useful benchmarks for future climates because it is characterized by a large increase in rainfall and land surface temperatures in northeastern (NE) Africa (Fig. 1a), due to stronger insolation and a larger ocean-continent warming differential. The estimated amount of rainfall brought by the monsoon during the AHP was higher by ca. 75% and is thought to have generated a three- to fivefold increase in Nile River runoff. The morphology of the Nile River itself was largely modified due to the development of a dense network of tributaries with a much larger drainage area. Geomorphologic evidence also points to the occurrence of episodes of violent rainfall and torrential floods, referred to as the “Wild Niles” period during the AHP, which probably led
prehistoric populations to abandon its banks\textsuperscript{15–17}. So far, the frequency and recurrence of these extreme runoff events has not been examined, which has limited our ability to identify the main driving factors.

![Map of humidity anomalies at 9 ka BP (9K) as compared to pre-industrial conditions (PI) estimated by the AWI-ESM model (see methods for more information), with the Nile River (pink) and the location of core P362/2-33 offshore the mouth of the Nile River (star).](image)

**Figure 1.** Precipitation in the Nile River watershed and varved record of core P362/2-33. (a) Map of humidity anomalies at 9 ka BP (9K) as compared to pre-industrial conditions (PI) estimated by the AWI-ESM model (see methods for more information), with the Nile River (pink) and the location of core P362/2-33 offshore the mouth of the Nile River (star). (b) Thickness record of four different sublayers corresponding to seasonal deposits (see legend) along the lithology and photograph of core P362/2-33\textsuperscript{9}.

Core P362/3-33 is ideally located to record annual changes in Nile flood dynamics during the AHP (Fig. 1a). This 6-m long sediment core was retrieved in 2008 on the western Nile deep-sea fan and contains a pristine 5-m long laminated sequence\textsuperscript{9,18} (Fig. 1b). The chronology was constrained using a combination of radiocarbon dating and annual layer (i.e., varve) counting. The radiocarbon ages were obtained on fossil planktonic foraminifera *Globigerinoides ruber* (white), which live in subsurface waters and provide a reliable estimation of depositional ages\textsuperscript{9,18}. Varve counting and measurements of sublayer thickness was realized under the microscope (Fig. 1). Microfacies revealed a repeating sequence of sublayers that was interpreted as a seasonal depositional cycle\textsuperscript{9}, which was used to determine the boundaries of annual layers. The annual deposition of the layers in core P362/3-33 was confirmed by fitting an autoregressive
gamma-walk sedimentation model based on a million Monte-Carlo simulations through eight radiocarbon ages (Extended Data Fig. 1). The excellent match between layer thickness expressed as accumulation rates and the probability distribution of radiocarbon ages confirms the presence of varves in core P362/3-33. In addition, this Bayesian model provides us with a very precise and accurate age determination with errors of ca. 100 yrs (max: 250 yr, min: 90 yr). Besides the so-called “Nilometer records” obtained by ancient Egyptians during the Common Era\textsuperscript{19}, our new record is the most detailed archive of past Nile floods.

**A continuous record of summer floods.** We obtained a continuous record of ca. 1500 varves between 9.47 and 7.94 ka BP. Another 70 varves occur above a non-laminated (bioturbated) interval between 7.69 and 7.62 ka BP (Fig 2a). Analyses of microfacies in core P362/3-33 showed that the flood layers have a specific facies related to terrestrial sediment-laden hyperpycnal deposits during seasonal floods of the Nile\textsuperscript{9,20}. The thickness of flood layers varies at annual to centennial timescales between 0.3 and 10 mm, with pronounced changes in the average thickness at ca. 8.08, 8.4, 8.62, 8.8, 8.88, 9.17 and 9.34 ka BP (± 0.05 ka) as indicated by changepoints in the sedimentation model (Fig. 2c, see Methods). These changes in flood-layer thickness occur within a few decades (ca. 30-40 yrs) and indicate large shifts in the volume of sediments deposited on the margin.

At our core site, the annual to centennial variability in flood layer thicknesses tracks sediment discharge and fluvial activity in the Nile watershed rather than spatial migrations of the depocenter or sea-level changes. The western part of the Nile deep-sea fan is a stable depocenter during the Quaternary\textsuperscript{21} and was particularly active between 15 and 6 ka BP\textsuperscript{22}. Available knowledge about sediment dynamics on the Nile Delta suggests a strong fluvial activity with the deposition of sandy units during the early Holocene\textsuperscript{23,24}. Local sea-level reconstructions obtained using an ensemble of three dimensional mantle-viscosity structures combined with the ICE6G glaciation history for the Nile deep-sea fan show a near-linear rise from about -18 to -2 m between 10 and 8 ka BP\textsuperscript{25}, with limited glacial-isostatic adjustments (Extended Data Fig. 4a). No significant relationship could be observed between flood-layer thickness and changes in rates of sea-level changes (Extended Data Fig. 4b), and we therefore posit that the post-glacial sea-level rise did not exert a substantial control on sediment dynamics over the western Nile deep-sea fan during the early Holocene.
Figure 2. Fluvial dynamics of the Nile River during the African Humid Period (7500-9500 yr BP). (a) Thickness of flood layers (grey curve), 30-yr moving average (dark blue curve) and 2-σ confidence (blue curves). (b) Number of strong and weak floods (respectively blue and orange curves) per 30 yrs (see Methods and Extended Data Fig. 2). (c) Median (thick dark blue line) and standard deviation (light blue line) of flood-layer thickness between changepoints. (d) Median grain-sizes (Log(D50), thick gold line) between changepoints. (e) Changepoints shown as probability density functions of sedimentation rate (N: number of iterations deviating from a linear accumulation rate).

By contrast, mean flood-layer thickness is significantly correlated to particle size (Fig. 2d), which suggests that our record faithfully tracks changes in flood strength. The link between layer thickness and flood strength, especially at annual scale, is not straightforward. Processes related to sediment storage and mobilization in large river systems can produce non-linearities between rainfall, flood strength and sediment discharge, whereby large (small) rainfall events might produce small (large) erosional episodes. Such nonlinearities are generally time-dependent (i.e.,
there is a lag between rainfall and sediment discharge signal) and are difficult to precisely pinpoint\textsuperscript{27,28}. Changes in the vegetation type and density in the catchment might also create non-linearities between rainfall amount and discharge\textsuperscript{29}. Notwithstanding these notes of caution, present-day observations lead credence to the capacity of large river systems such as the Nile to faithfully generate and transfer climate-induced signals to the sink\textsuperscript{26,30}. This is particularly true for large flood events during which considerable volumes of sediment are rapidly eroded upstream, transported and deposited offshore. At present, the amount and grain-size of particulate matter measured in the main branch of the Nile River is directly related to the onset of summer monsoon rains over the Ethiopian Highlands, at the source of the Blue Nile\textsuperscript{31,2}.

Therefore, even if a direct link between flood-layer thickness and flood strength cannot be established on an annual basis, we can confidently use our record to inform past flood dynamics on interannual to decadal timescales.

**Catastrophic floods and flickering fluvial regimes.** Our new annual record of flood layer thickness provides evidence for the occurrence of extremely strong floods during the AHP and allows us to explore the sub-decadal dynamics of the Nile River under higher rainfall conditions. A prominent pattern in our record is the occurrence of thicker flood layers between 9.4 and 8.6 ka BP (Fig. 2a), depicting a period of strong erosional activity in the Nile River basin and the deposition of large amounts of particulate matter offshore. The volume of sediments transported in this interval was on average two to three times higher than after 8.6 ka BP (Fig. 2c). This order of magnitude is similar to previous estimations of increases in heavy rainfall frequency and Nile runoff during the AHP\textsuperscript{12,17,32}, suggesting that rainfall intensity might exert a substantial control on the erosional activity in the Nile watershed.

In addition to strong floods, the time interval between 9.4 and 8.6 ka BP is characterized by an increase in the number of extreme (strong and weak) floods (Fig. 2b). The flood layer thickness in this interval has a much wider distribution as compared to intervals with lower median thickness (Fig. 2c). The frequency of stronger-than-normal and weaker-than-normal floods increases in parallel, although the number of strong floods is generally higher than the number of weak floods (Fig. 2b). Our results suggest that highly erosional periods were associated to high levels of interannual variability in fluvial dynamics, and lend credence to the forecasted stronger Nile flow variance under future warmer and wetter conditions\textsuperscript{7}.
Another striking observation is the occurrence of rapid changes in fluvial regime as seen by the existence of changepoints in the accumulation rates (Fig. 2c). These changes typically occur within 30-70 yrs and are characterized by significant modifications of the erosion regimes in the Nile watershed, leading to the deposition of flood layers with thickness of different median and variance (Fig. 2c). Such rapid switches cannot be readily attributed to a single driver but might result from threshold-like responses of the Nile River to climatic or environmental changes. The observed signal might result from changes in moisture source and monsoonal dynamics affecting the amount and variability of the rainfall\footnote{33}. However, other factors such as changes in vegetation cover\footnote{34} or fluvial morphology (e.g., the activation and abandonments of tributaries, especially those located at the northern border of the monsoonal cells)\footnote{13,17} might also lead to nonlinear erosional responses.

**Inferences on the drivers of flood dynamics under intensive rainfall.** Most of our understanding of flood dynamics in a warmer world derives from modelling experiments, whereby different types of models can provide diverging results\footnote{35}. In particular, the predictability of interannual to centennial-scale changes in flood dynamics in warmer climates remains challenging\footnote{36}. Obtaining benchmarks from past geological intervals is therefore of crucial importance to capture the full range of natural climatic variability and improve the skillfulness of models to predict future changes\footnote{37}. In that respect, our annually-resolved record provides a unique opportunity to determine the main climatic forcing and the cyclicity of Nile floods at timescales ranging from annual to centennial during the wetter and warmer AHP. Thanks to the existence of long-term monitoring of past Nile levels by ancient Egyptians during the Common Era (the so-called “Nilometer” records)\footnote{19}, which have a similar time-span and resolution as our record, we can determine the influence of different climatic backgrounds on flood variability.
Figure 3. Comparison of oscillatory regimes between the Common Era and the early Holocene African Humid Period. (a) Multi-tapper analysis of the log-transformed Nilometer data with the periodogram (black), harmonics (blue) and significance levels against a red noise background (90%: red; 95%: light blue; 99%: green). Significant periodicities above the 99% confidence level are indicated in blue and above 95% in green and italic. (b) Wavelet (Morlet of wavenumber 6) analyses of the detrended and log-transformed record of high Nile flow from the Nilometers covering the past 1300 yrs, with p=0.05 significance levels against a red noise in orange (lag=0.9), cone of influence overlain. ENSO band is indicated in the wavelet plots by red rectangles. (c) Multi-tapper analyses of the log-transformed flood thickness record of core P362-2-33 covering the time interval 7.5-9.5 ka BP. (d) Wavelet analyses of the detrended and log-transformed summer flood thickness record of core P362/3-33. See Methods and Extended Data Fig. 5-7 for more details on time-series detrending and normalization.

Once detrended and normalized, both records from the AHP and the Common Era were analysed using wavelet and multi-tapper methods to detect significant oscillatory regimes (see Methods and Extended Data Fig. 5-7). In both records, a significant signal is found in the interannual range with persistent periodicities between 2 and 7 yrs throughout the time intervals (Fig. 3). This oscillatory mode is a clear fingerprint of El Niño-Southern Oscillation (ENSO), which has been shown to drive NE African hydroclimates both at present and during the Common Era. This teleconnection operates through complex ocean-atmospheric interactions that control the zonal moisture (Walker) circulation. La Niña phases (i.e., a cooler eastern Pacific) are associated with enhanced rainfall and widespread flooding in the NE African monsoonal realm, while El Niño phases are associated with droughts and negative anomalies of...
precipitation\textsuperscript{41}. The persistence of the ENSO oscillatory mode during the AHP demonstrates the stationarity of the Pacific-NE Africa teleconnection in warmer and wetter climates\textsuperscript{42}. This result provides a crucial fundament for modelling experiments and projections of ENSO-driven climatic and environmental change in a warmer world\textsuperscript{43}.

A particularly strong ENSO fingerprint is observed during the interval of intense flooding between 9.2 and 8.5 ka BP (Fig. 3d), which is characterized by the highest amplitude and variability in erosion dynamics (Fig. 2b-c). At a first glance, this observation might suggest that the large interannual variability of Nile floods reflected a larger ENSO variance during the early Holocene. However, records of past ENSO variability show strong discrepancies for the early Holocene\textsuperscript{44}, with records pointing either to higher or unchanged ENSO amplitude\textsuperscript{45,46} or to a dampened ENSO as compared to the present\textsuperscript{47,48}. Due to the lack of consensus, changes in the flood variance cannot be unequivocally attributed to ENSO variability. In fact, enhanced rainfall amplitude might readily result from regional amplification of the natural climatic variability under warmer conditions\textsuperscript{6,49}. According to modelling experiments, both the mean rainfall and extreme precipitation events will increase due to the thermodynamic (warming-related) increase in atmospheric moisture\textsuperscript{6}, which matches our observations of flood dynamics during the AHP (Fig. 2c). Simulations of ocean and atmosphere state at 9K suggest a shift of sea surface conditions toward La Niña (cooler eastern Pacific, Extended Data Fig. 9), which would explain the occurrence of heavy flooding in the Nile Valley.

Decadal to centennial-scale oscillatory modes are also identified in both records from the Common Era and the AHP (Fig. 3a,c). Periodicities related to the solar cycles dominate the range 11-22 yr (sunspot and Hale cycles) and are widely identified in annually-resolved records\textsuperscript{50,51}. Two robust periodicities are detected at ca. 54-55 and 93-100 yrs in both records. These signals could be related to the solar Gleissberg cycles (90 yrs) or to a climatic mode such as the Pacific decadal oscillation (PDO, which can interact with ENSO and has a 50-70 yrs periodicity\textsuperscript{52}) or the Atlantic multi-decadal oscillation (AMO, which has been shown to influence precipitation in North Africa and has a 40-60 yrs periodicity\textsuperscript{53}). An unequivocal attribution of a climatic mode to the observed multi-decadal and centennial periodicities is not possible. However, our results provide new insights on low-frequency modulation of flood dynamics in the Nile Basin. First, similarly to the high-frequency oscillatory modes, the low-frequency modes identified during the Common Era also occur in warmer and wetter conditions of the African Humid Period (Fig.}
3a,c). Second, multi-decadal and centennial oscillatory modes appear to be driving the changes in flood extremes (Fig. 4). Bandpass filters applied to the log-transformed flood records of the Common Era and the AHP show that the number of extreme flood events is largely modulated by oscillations in the multi-decadal timescales. Despite being widely identified in climate records, the drivers of this multi-decadal variability remain elusive and difficult to capture in global climate models. We show here that in the Nile fluvial system, this variability occurs consistently in time intervals with different climatic background and that it might play an essential role to modulate the occurrence of extreme floods.

Figure 4. Multi-decadal variability drives extreme flood events during similar and wetter-than-present conditions. (a) Number of extreme flood events per 30 yrs bins (blue: strongest floods, orange: weakest floods) in the high Nile level records (Nilometer) during the Common Era, compared to the filtered log-transformed record of high Nile flood levels (pink). (b) Similar comparison for the flood thickness record (Nile deep-sea fan) of the African Humid Period. See Methods for more information on bandpass filtering and data processing; number of extreme floods as in Fig. 2b.

In the context of a rapidly changing climate, annually-resolved records from past warm intervals can provide timely insights about the response of natural systems to warmer conditions at human-relevant timescales. In particular, capturing the full range of natural climatic variability
in flood records is crucial to build reliable forecasting tools. Regular flooding in the Nile River is essential for the subsistence of dense populations in NE Africa but is also the source of important environmental and political pressure (flooding, trans-border conflicts)\(^8\). We provide here sedimentary evidence of a highly variable river with extremes in flood intensity and strong erosive events, in short a “Wild Nile”, during the AHP. It is suggested that such an environment was inhabitable for prehistoric populations\(^16,17\). Our new record helped to identify climatic and oscillatory modes that operated during the Common Era and the AHP, which have different climatic backgrounds. The stationarity of high- and low-frequency signals provides a strong basis for testing hydrological models incorporating this climatic variability. However, the existence of non-linearities in the river response to multi-centennial oscillations leading to rapid switches in erosion regime calls for further research. Finally, our data show that the volume of sediments transported and deposited offshore the Nile River vary by a factor 2 to 3 throughout the record (Fig. 2c). Assuming that sediment transport is, on interannual to decadal timescales, directly related to river flow, our observations provide relevant benchmarks for scaling future infrastructure.

References


Methods

**Microfacies description in core P362/2-33.** Core P362/2-33 contains ca. 5 m of finely laminated sediments that consist of alternating dark- and light-coloured millimetre-thick layers. The microfacies and their chemical composition have been described in details in Blanchet et al.\(^9\) and we present here the whole-core thickness measurements for each sublayer type (Fig. 1b). A regular sequence of four types of sublayers occurs throughout the core with two of them being always present. These sublayers have been associated with seasonal depositional regimes: 1) summer floods, 2) autumn blooms (plankton), 3) winter runoff, and 4) authigenic carbonates. Summer flood sublayers are characterized by coarser detrital grains and high Ti/K ratios while winter runoff consists of clay-sized, low Ti/K sediments\(^9\). Autumn blooms occur after the summer flood and are characterized in core P362/2-33 by the presence of planktonic foraminifera shells. Such blooms were observed during historical Nile floods\(^54\). Authigenic carbonates are fined-grained calcite deposits that are interpreted to form in the bottom waters due to anoxic to sulfidic conditions at the end of the spring\(^9\). Several event layers were also identified in the core as matrix-supported layers and associated to large-scale remobilization episodes or large flood events\(^20\). Their facies is clearly distinct from that of the summer flood sublayers. The summer flood and winter runoff deposits are the main contributor to the total layer thickness (Fig. 1b). Large changes in the layer thickness of all sublayers are observed throughout the record, with thicker sublayers between ca. 9.2 and 8.7 ka BP.

**Age modelling.** In order to estimate the age-depth relationship in core P362/2-33, we used 11 radiocarbon ages measured on planktonic foraminifera *Globigerinoides ruber* that were published in Blanchet et al.\(^18\). The radiocarbon ages were calibrated using the Marine20 calibration curve, which already contains corrections for reservoir ages\(^55\).

We constructed the age model using a Bayesian age-depth modelling approach, which leverages relative age information from varve counting as prior information to model absolute age information from radiocarbon dating. The basic aim of this approach is to integrate the two sources of information and obtain a more accurate and precise age-depth relationship. Specifically, we used the varve counts to inform the prior distribution of ages at each depth interval, and then updated this distribution using the radiocarbon dating data. By combining these two sources of information, we were able to produce a robust and reliable age-depth model for core P362/2-33.
To incorporate varve counts into a parameterized model for accumulation rates, we employed autoregressive gamma walks, as proposed by Blaauw and Christen\textsuperscript{56}. The general form of autoregressive gamma walks is given by

$$x_i = \omega x_{i+1} + (1 - \omega) \gamma$$

where $x_j$ is the accumulation rate (in yr/cm) in depth interval $j$ (with constant spacing $\Delta c$), $\omega$ is the autocorrelation at lag 1 and $\gamma$ is a gamma distributed random variable with mean $a$ and shape $b$ ($\gamma \sim \text{Gamma}(a, b)$). To take the pronounced changes in accumulation rates of core P362/2-33 into account, we subdivided the sequence of varve counts into sections with similar mean accumulation rates using the Pruned Exact Linear Time (PELT) changepoint detection algorithm by Jackson et al.\textsuperscript{57}. Subsequently, the three parameters $\omega_d$, $a_d$ and $b_d$ were estimated for each section $d$. The resulting model was realized $10^6$ times and each realization randomly anchored to the probability distribution of the youngest radiocarbon age (Extended Data Fig. 1, light blue area). Subsequently, we updated the ensemble of model realization by selecting age-depth relations maximizing the correspondence to radiocarbon ages (dark blue areas in Extended Data Fig. 1). This optimization process allows us to identify the most probable varve stratigraphy given the absolute age information of radiocarbon dates and quantify the uncertainty in the age estimates.

The modelled age-depth relationship falls within the uncertainty of all the 11 radiocarbon dates (Extended Data Fig. 1). This allows us to build an accurate age model with a high precision (uncertainties are below 100 yr) and to maintain the high precision level throughout the profile. The excellent match between accumulation rates derived from varve counting and radiocarbon measurements also confirms the hypothesis that the sequence of four sublayers represent an annual cycle and therefore real varves.

**Data analysis.** In order to analyse the data, we used well established statistical parameters. Following Lawman et al.\textsuperscript{48}, we have calculated the amount of extreme event (high or low flood) per 30 yr on both the flood layer thickness record of core P362/2-33 (Extended Data Fig. 2c) and the Nilometer (high Nile) levels (Extended Data Fig. 3c)\textsuperscript{38}. However, because our data of flood thickness are constrained (i.e., cannot be negative), we have used the log-transformed records and applied a 9-yr high-pass filter using the FIR filters in the Past4 software\textsuperscript{58} (Extended Data Fig. 2b, 3b). Extreme events are defined as values higher (lower) than the 95 (5) percentiles.
We then calculated the moving number of extreme high and low floods per 30-yr window (Extended Data Fig. 2c, 3c). Extended Data figure 2e shows the distribution of probable ages for the estimated changepoints (see “Age modelling”) in the final age model. The histograms represent the number of changepoints detected by a million Monte-Carlo models, which allows us to provide an estimation of uncertainty around each changepoint and a determination of the skewness of the changepoint distribution. The raw flood layer thicknesses were then split in seven parts between the changepoints and the changes in median and standard deviation were calculated (Extended Data Fig. 2d). These analyses show a doubling of the median thickness between different parts of the record, with thicker layers associated to a higher standard deviation than thinner layers.

**Glacial Isostatic Adjustment modelling.** We used outputs from the 3D glacial isostatic adjustment (GIA) model VILMA (VIscoelastic Lithosphere and MAntle Model) to evaluate the changes in relative sea level (RSL) at the core site (29°50'E/31°36'N). This model ensemble allows us to test the effect of upper-mantle and asthenosphere viscosity structure on post-glacial sea-level rise according to the ICE6G glaciation history. The computed RSL variations show a near linear rise from -18 to -2 m with very little effect of mantle viscosity structures (Extended Data Fig. 4a). After averaging the 18 model outputs (ensemble mean), we calculated the first derivative, which tracks the changes in rates of RSL changes. Finally, we calculated the median values of log-transformed RSL rates between changepoints in order to compare them to mean changes in flood-layer thickness (Extended Data Fig. 4b).

**Grain-size measurements.** The distribution of siliciclastic grains was measured at the University of Innsbruck on a set of 80 samples (Ramisch et al., in prep.). After being rinsed three times with ultrapure water (MilliPore\textsuperscript{R} system), sediments were decarbonated using buffered acetic acid and the organic matter was removed using concentrated hydrogen peroxide. All solutions were prepared fresh in the clean lab at GFZ Potsdam using ultrapure acids. Samples containing the siliciclastic fraction were then shipped to Innsbruck, where they were mixed with sodium pyrophosphate to avoid the formation of clay aggregates and measured in triplicate on a Malvern Mastersizer 3000.

The results show grain-sizes ranging between 0.1 and 100 µm with main modes at ca. 0.5-0.6 and 3-4 µm (not shown), very similar to results obtained on this sediment core previously at low resolution. For the present study, we report the median grain size (D50), which is modulated by hydrodynamic sorting and flow strength. The data are presented as individual samples.
(Extended Data Fig. 4d) and as log-transformed averages (median) computed between changepoints (Extended Data Fig. 4c). Comparing data located in different data spaces (only positive, unconstrained) in a log-log space allows us to compute linear regressions and estimate their statistical significance.

**Time-series analysis.** To investigate the frequency domain of our annual record of past Nile flow, we used time-series analysis performed on the so-called Nilometer records of the Common Era, which are also annually-resolved\(^3^8\). We present here the multi-tapper method results performed on the Nilometer and Nile deep-sea fan records using the online SSA-MTM toolkit version 4.4\(^6^0\). The MTM analysis was performed on the raw (raw, Extended Data Fig. 5), log-transformed (log, Extended Data Fig. 6) and differentiated log-transformed (log\[x_t/x_{t-1}\]) (log(diff), Extended Data Fig. 7) flood-layer thickness and high-Nile level data with a resolution of 3 and 5 tappers. The SSA-MTM toolkit allows us to detect harmonics (in blue) and frequencies significant at the 90, 95 and 99% confidence level against a red-noise background. These analyses show that both records contain significant frequencies in the range 2-7 yr, which are typical of El Niño-Southern Oscillation (ENSO). The results for the high-frequencies (inter-annual range) are similar for the raw, log and log(diff) data, but the log(diff) spectra is distinctly “blue” (Extended Data Fig. 7a,c) compared to the “red” spectra for raw and log data (Extended Data Fig. 5a,c; 6a,c). This is due to the fact that the log(diff) procedure filters lower frequencies out of the signal. Significant frequencies are observed in the multi-decadal range for the log data (Extended Data Fig. 6a,c) whereas the spectra for the raw data are saturated for centennial ranges (Extended Data Fig. 5a,c). The raw data being constrained (always positive), we favour the log-transformed data for interpreting the MTM spectra (Extended Data Fig. 6a,c), which allow us to examine the non-detrended but unconstrained signals.

Another useful method to detect ENSO fingerprints in time-series is wavelet analyses\(^3^9\). We used the software PAST to perform a continuous wavelet transform\(^5^8\), using a Morlet wavelet of wavenumber 6, on the raw (Extended Data Fig. 5b,d), log (Extended Data Fig. 6b,d) and log(diff) data (Extended Data Fig. 7b,d). Strong signals are detected in the frequency bands between 2-7 yr in all wavelet analysis. Signal power corresponds to the correlation strength to the mother wavelet is indicated by the colour coding (yellow: high, blue: low)\(^6^1\). Signal powers above the p=0.05 significance level above the null hypothesis of a red noise (Lag=0.9) are highlighted in red and cones of influence (delimiting the regions with boundary effects) are superimposed in the lower corners of the plots. For further interpretations, we favour the
log(diff) records (Extended Data Fig. 7b,d), which allow us to explore variability in the interannual range on unconstrained records where the autocorrelation effects were removed. **Numerical modelling.** We used numerical simulations from several sources to estimate the changes in rainfall over NE Africa for the next century and during the African Humid Period (AHP). To elucidate the spatial distribution of precipitation for different warming scenarios, we analysed the simulations for end-of-the-century precipitation distribution (modelled ensemble mean precipitation) based on the sixth phase of the Coupled Model Intercomparison Model (CMIP6)\(^6^2\). We compared simulations for the Shared Socioeconomic Pathways (SSP) 1-2.6 (CMIP6-SSP126), 2-4.5 (CMIP6-SSP245), 3-7.0 (CMIP6-SSP370) and 5-8.5 (CMIP6-SSP585) to the 1850-2010 baseline (CMIP6-Historical) (Extended Data Fig. 8). These four scenarios vary between the low-end emission (“taking the green road” - SSP126) to the high-end emission (“taking the highway”, SSP585) scenarios, respectively\(^6^3,6^4\). The scenario emissions are anticipated to produce a radiative forcing in 2100 of approximately 2.6 \(\text{w m}^{-2}\) in SSP126 due to an increasing shift toward sustainable practices, and 8.5\(\text{w m}^{-2}\) in SSP585 due to a fossil-fuel driven development. The mean seasonal precipitation (August-September-October) has been computed for the ensemble mean following four warming scenarios according to the SSP (Extended Data Fig. 8).

Then, in order to determine whether the rainfall patterns during the AHP can be used as analogues of predicted monsoon changes in warmer and wetter climates, we also used simulations performed using the Alfred-Wegener Institute-Earth System Model (AWI-ESM) for climatologies at 9 ka BP (9K) to evaluate the rainfall dynamics over Eastern Africa during the African Humid Period (Extended Data Fig. 9). These simulations were performed using the boundary conditions as defined in Shi et al.\(^6^5\), with orbital parameters, greenhouse gases and ice sheets set at 9K and an integration time of 800 yr. The simulations depict an increase in summer rainfall in the monsoon region over North Africa (Extended Data Fig. 9a,b), and a Pacific Ocean configuration similar to La Niña conditions (Extended Data Fig. 9c).

In order to test the reliability of the modelling experiment for estimating the rainfall dynamics in the Nile sources, we computed monthly mean of daily precipitation in control runs for both the AWI-ESM and the CMIP6 ensemble and compared these to the observed annual rainfall cycle obtained from the Climatic Research Unit (CRU TS4) (Extended Data Fig. 10)\(^6^6\). Both the AWI-ESM and the CMIP6 ensemble mean capture well the seasonal rainfall dynamics but tend to underestimate rainfall in spring and autumn in the AWI-ESM and in summer in the CMIP6
ensemble mean (Extended Data Fig. 10a,b). The summer precipitation is largely enhanced in the 9K simulation, whereas the CMIP6 ensemble mean shows a stronger rainfall anomaly at the end of the wet season (August-September) (Extended Data Fig. 10c-e). It is remarkable that the summer rainfall anomaly is very similar for the 9K and warmest SSP585 scenario (Extended Data Fig. 10e). The cumulative annual rainfall falls in similar ranges for the simulations at 9K and in SSP scenarios (Extended Data Fig. 10d).

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Table 1. Models used in the CMIP6 experiment and their associated references.

References:


Acknowledgments: The authors thank J. Mingram and B. Brademmann for assistance with microscopy and preparation of samples, respectively. We also thank Hannah Braun and Jasper Moernaut for their help with measurements of grain-size distributions. Earlier versions of this work have been discussed with colleagues in conferences and seminars, whom we acknowledge collectively. We would like to thank also Dr. Xiaoxu Shi for making available the AWI-CM runs.

Funding: This work was initiated by CB during a reintegration grant funded by the GFZ Potsdam (2018-2020). Further funding was provided to MB, VK, CB, AR and AB by the German Climate Modeling Initiative PalMod funded by the German Ministry of Education and Research (Bundesministerium für Bildung und Forschung, FKZ 01LP1910A, 01LP1918A) and to RT, MI and AB through the Helmholtz Association joint program “Changing Earth – Sustaining our Future” (PoF IV). MI and AB also acknowledge support from the Helmholtz Climate Initiative REKLIM.

Author contributions: The research was conceptualised by CB, who performed the sampling, microfacies identification and varve counting. CB, AR and RT performed the statistical and data
analyses, AR also provided the Bayesian age modelling framework. LL, CB and AR prepared and performed the grain-size analyses. MI designed and analysed the numerical model outputs. MB and VK provided simulations of the 3D glacial-isostatic adjustment model VILMA as well as background knowledge on RSL changes. CB wrote the original draft and all authors contributed to the revision of the manuscript.

Competing interests: Authors declare that they have no competing interests.

Data and materials availability: The data presented here are available for reviewers during the peer-review process (link provided to editorial team) and will eventually be deposited and fully accessible in the Varved Sediment Database VARDA (https://varve.gfz-potsdam.de/database).
Extended Data figures

Extended Data Fig. 1. Age-depth model for core P362/2-33. Orange violin distributions: radiocarbon ages measured on planktonic foraminifera *G. ruber* recalibrated using MARINE20 (and no correction for reservoir age). The white curve is the accumulation rate profile from layer counting and thickness measurement tied to the youngest radiocarbon age, with 2-sigma uncertainty in light blue. Dark blue represents the Monte-Carlo for potential age-depth models respecting the age accumulation prior and radiocarbon dates.
Extended Data Fig. 2. Data analysis of the flood layer thickness of core P362/2-33. (a) raw flood thickness (grey) with the 30-yr moving median (dark blue) and the 1-sigma uncertainty (light blue). (b) logarithm of flood thickness, filtered with a high-pass 9-yr filter (dark grey) with 95 and 5 percentiles (orange dashed lines). (c) number of extreme events per 30 yr moving
Extended Data Fig. 3. Data analysis of high Nile levels from the Nilometers\textsuperscript{38}. (a) Raw high Nile levels (grey) with the 30-yr moving median (dark purple) and the 1-sigma uncertainty (light purple). (b) Logarithm of high Nile levels, filtered with a high-pass 9-yr filter (dark purple) with 95 and 5 percentiles (orange dashed lines). (c) Number of extreme events per 30-yr moving window, with highest floods (purple) and lowest floods (orange).
Extended Data Fig. 4. Comparison of flood thickness with relative sea-level changes and grain-size distributions. (a) Changes in relative sea-level (RSL) from the 3D glacial adjustment model (GIA) VILMA (see methods) for different viscosity structures at the location of the Nile deep-sea fan (colour coding as in ref.25). Changes in the rate of RSL between changepoints, calculated from ensemble mean of GIA simulations as median values of log-transformed RSL
rate (black thick line) (see methods). **(b)** Median values of log-transformed flood-layer thickness between changepoints (blue thick line) and relationship between flood-layer thickness and RSL rates (bi-plot). The relationship between flood-layer thickness and RSL changes is considered non-significant since the calculated p-value is higher than 0.005 and the error around the regression are very large (blue shading). **(c)** Averaged (median) values of median grain-sizes (D50) between changepoints (yellow thick line) calculated from (e) and relationship between flood-layer thickness and median grain-size (bi-plot). **(d)** Flood-layer thickness (grey) with the 30-yr moving median (dark blue) and the 1-sigma uncertainty (light blue). Median grain-sizes (D50) for 80 discrete samples (yellow diamonds). The relationship between flood-layer thickness and grain-size is considered significant since the p-value is equal to 0.05 and the error around the regression (orange shading) is small. The location of changepoints (see Extended Data Fig. 3) is shown as dashed lines with uncertainties as grey bars.

**Extended Data Fig. 5. Time-series analyses for the raw Nilometer and Nile deep-sea fan records.** **(a)** Multi-tapper analysis of the raw high Nile levels record during the Common Era...
(Nilometer data) with the periodogram (black), harmonics (blue) and significance levels against a red noise (90%: red; 95%: light blue; 99%: green). Red box: zoom on the 2-10 periodicity range. Significant frequencies above the 99% confidence level are indicated in blue, those above 95% in green italic. (b) Plot of the high Nile levels on the age scale (blue curve) and its continuous (Morlet) wavelet transform with signal power indicated by the colour coding (left hand-size) and periodicities on the y-axis. Signal power is color-coded (yellow-blue for high-low) and powers above the p=0.05 significance level above a red noise are shown as orange underlines. Cones of influence represent areas where periodicities are not significant and are superimposed in the lower corners of the plots. (c, d) same as (a, b) for the raw flood-layer thicknesses on the Nile deep-sea fan during the African Humid Period (this study).

Extended Data Figure 6. Time-series analyses for the log-transformed Nilometer and Nile deep-sea fan records. Same as in Extended Data Fig.4 but for the log-transformed (log[x]) high Nile levels record during the Common Era and log-transformed flood layer thicknesses from the Nile deep-sea fan during the African Humid Period.
Extended Data Figure 7. Time-series analyses for the log-transformed and differentiated Nilometer and Nile deep-sea fan records. Same as in Extended Data Fig.4 but for the logarithms of differentiated \(\log(x_t/x_{t-1})\) high Nile levels record during the Common Era and the logarithms of differentiated flood layer thicknesses from the Nile deep-sea fan during the African Humid Period.
Extended Data Figure 8. Ensemble mean of the seasonal [(August – September – October (ASO))] precipitation anomaly over the period 2051 -2100 relative to 1981-2010 based on (a) SSP126; (b) SSP245; (c) SSP370 and (d) SSP585. A list with the models used to compute the ensemble mean can be found in methods table 1.
Extended Data Figure 9. Ensemble mean of the seasonal [(August – September – October (ASO)] anomalies during the early Holocene (9K) relative their corresponding control.
experiments (PI) (a) Simulated large-scale precipitation anomalies; (b) Sea level pressure anomalies and (c) Sea surface temperature anomalies.

Extended Data Figure 10. Annual rainfall dynamics in CMIP6 mean ensemble and 9K simulations of the AWI-ESM model as compared to observations (CRU) for the region 5-20°N, 25-45°E. (a) Monthly mean of daily precipitation for the control runs, preindustrial (PI) for the AWI-ESM (green) and historical times (clim) for the CMIP6 ensemble mean (blue) and for the observation (CRU). (b) Monthly mean of daily rainfall anomalies between control runs and observations. (c) Monthly mean of daily precipitation for simulations at 9K with AWI-ESM (green) and for several SSP scenarios in the CMIP6 ensemble mean (blue). (d) Cumulative annual rainfall as in A and C. (e) Monthly mean of daily precipitation between simulation and control runs, simulations at 9K-PI for the AWI-ESM (green) and between forecasts in the SSP scenarios-historical period (clim) in the CMIP6 ensemble mean (blue).